Neutrinos as a Diagnostic of High Energy Astrophysical Processes

Luis A. Anchordoqui,[1] Haim Goldberg,[1] Francis Halzen,[2] and Thomas J. Weiler[3]

[1]*Department of Physics, Northeastern University, Boston, MA 02115*
[2]*Department of Physics, University of Wisconsin, Madison WI 53706*
[3]*Department of Physics and Astronomy, Vanderbilt University, Nashville TN 37235*

A leading candidate for the extragalactic source of high energy cosmic rays is the Fermi engine mechanism, in which protons confined by magnetic fields are accelerated to very high energy through repeated scattering by plasma shock fronts. In the process of acceleration, collisions of trapped protons with the ambient plasma produce pions which decay to electromagnetic energy and neutrinos. For optically thin sources, a strong connection between the emerging cosmic rays and secondary neutrinos can be established. In this context, we show the feasibility of using the Glashow resonance as a discriminator between the pp and $p\gamma$ interactions in Fermi engines as sources of neutrinos. In particular, we demonstrate how three years of observation at the km^3 IceCube facility can serve as a filter for the dominance of the pp interaction at the source.

Neutrinos can serve as unique astronomical messengers. Except for oscillations induced by transit in a vacuum higgs field, neutrinos propagate without interactions between source and Earth, providing powerful probes of high energy astrophysics [1]. The deployment of the km^3 IceCube facility at the South Pole [2] will greatly increase the statistics required for the realization of such a program.

The flavor composition of neutrinos originating at astrophysical sources can also serve as a probe of new physics in the electroweak sector [3]. Specifically, IceCube will have the capability to clearly identify neutrino species [4], and consequently will be able to measure deviations of flavor composition from standard expectations. In addition, in resonant scattering $\overline{\nu}_e e^- \to W^- \to$ anything [5], the detector can simultaneously discriminate between ν_e and $\overline{\nu}_e$. In this Letter, we show that the signal for $\overline{\nu}_e$ at the Glashow resonance, when normalized to the total $\nu+\overline{\nu}$ flux, can be used to differentiate between the two primary candidates ($p\gamma$ and pp collisions) for neutrino-producing interactions in optically thin sources of cosmic rays.

It is helpful to envision the cosmic ray engines as machines where protons are accelerated and (possibly) permanently confined by the magnetic fields of the acceleration region. The production of neutrons and charged pions and subsequent decay produces both neutrinos and cosmic rays: the former via $\pi^+ \to e^+\nu_e\nu_\mu\overline{\nu}_\mu$ (and the conjugate process – more on this below), the latter via neutron diffusion from the region of the confined protons. If the neutrino-emitting source also produces high energy cosmic rays, then pion production must be the principal agent for the high energy cutoff on the proton spectrum [6, 7]. Conversely, since the protons must undergo sufficient acceleration, inelastic pion production needs to be small below the cutoff energy; consequently, the plasma must be optically thin. Since the interaction time for protons is greatly increased over that of neutrons because of magnetic confinement, the neutrons escape before interacting, and on decay give rise to the observed cosmic ray flux. A desirable property of this low-damping scenario is that a single source will produce cosmic rays with a smooth spectrum across a wide range of energy.

For optically thin sources, the neutrino power density scales linearly with the cosmic ray power density $\dot{\epsilon}_{\rm CR}$ [8]. The actual value of the neutrino flux depends on what fraction of the proton energy is converted to pions (which then decay to neutrinos and photons). To quantify this, here we define ϵ_π as the ratio of pion energy to the emerging nucleon energy at the source. Since there is about one cosmic ray (neutron) produced per proton collision, a significant consequence of the neutron leakage model is that ϵ_π is expected to be approximately equal to the fraction of collision energy carried off by pions in a single collision. Following Waxman and Bahcall [8], the expected total (all species) neutrino flux is

$$E_\nu^2\, \Phi^{\rm total}_{\nu+\overline{\nu}} \approx 2\times 10^{-8}\ \epsilon_\pi\, \xi_z\ {\rm GeV\ cm^{-2}\ s^{-1}\ sr^{-1}}\ , \quad (1)$$

where for no source evolution $\xi_z \approx 0.6$, whereas for an evolution $\propto (1+z)^3$ as seen in the star-formation rate, $\xi_z \approx 3$ [9].

Depending on the relative ambient gas and photon densities, pion production proceeds either through inelastic pp scattering [10], or photopion production predominantly through the resonant process $p\gamma \to \Delta^+ \to n\pi^+ \,{\rm or}\, p\pi^0$ [8]. For the first of these, pion production is well-characterized by a central rapidity (Feynman) plateau, yielding $\epsilon_\pi \approx 0.6$ [11]. For resonant photoproduction, the inelasticity is kinematically determined by requiring equal boosts for the decay products of the Δ^+ [12], giving $\epsilon_\pi \approx 0.25$ [13].

The first production mechanism (described above) involves the dominance of inelastic pp collisions in generating charged pions. The nearly isotopically neutral mix of pions will create on decay a neutrino population in the ratio $N_{\nu_\mu} = N_{\overline{\nu}_\mu} = 2N_{\nu_e} = 2N_{\overline{\nu}_e}$. In propagation to Earth, a distance longer than all oscillation lengths, flavor-changing amplitudes are replaced by probabilities [14], resulting in equal fluxes for all six neutrino species, so that $N^{\rm Earth}_{\overline{\nu}_e} = \frac{1}{6}\, N^{\rm total}_{\nu+\overline{\nu}}$. Here, we have incorporated maximal $\nu_\mu \leftrightarrow \nu_\tau$ mixing and the known smallness of $|\langle\nu_e|\nu_3\rangle|^2$, where $\nu_3 \simeq (\nu_\mu+\nu_\tau)/\sqrt{2}$ is the third neutrino eigenstate.

The second mechanism proceeds via photoproduction of pions by trapped protons on the thermal photon background, leaving the isotopically asymmetric process $p\gamma \to \Delta^+ \to \pi^+ n$ as the dominant source of neutrinos. At production, $N_{\nu_\mu} = N_{\overline{\nu}_\mu} = N_{\nu_e} \gg N_{\overline{\nu}_e}$. After oscillation, the $\overline{\nu}_e$ flux at Earth is

$$\begin{aligned} N_{\overline{\nu}_e}^{\rm Earth} &= N_{\overline{\nu}_\mu}\, P(\overline{\nu}_\mu \to \overline{\nu}_e) \\ &= \frac{1}{3}\, \sin^2\theta_\odot\, \cos^2\theta_\odot\, N_{\nu+\overline{\nu}}^{\rm total} \quad . \end{aligned} \tag{2}$$

Using the most recent SNO value of the solar mixing angle $\theta_\odot \simeq 32.5°$ [15], we obtain $N_{\overline{\nu}_e}^{\rm Earth} = \frac{1}{15}\, N_{\nu+\overline{\nu}}^{\rm total}$. Because of averaging over various thermal environments, this relation holds across the neutrino spectrum [8].

The preceding discussion indicates the feasibility of differentiating between the two processes as follows: *(i)* obtain a normalization for the total flux from data outside the Glashow resonance region; *(ii)* measure the event rate in the resonance region, and compare with the ratios given above. In what follows, we will assess the potential of IceCube to obtain a statistically significant signal-to-background ratio.

The cross section for Glashow resonant scattering reads

$$\sigma = \frac{\pi}{2m_e\, E_\nu}\, |\mathfrak{M}|^2\, \delta(2m_e E_\nu - m_W^2)\ , \tag{3}$$

where $|\mathfrak{M}|^2 = g^2 m_W^2/2$, m_e and m_W are the electron and W masses, and $g^2 = 4\pi\alpha(m_W)/\sin^2\theta_{\rm W}(m_W) \simeq 0.43$. Now, for an incoming flux of antineutrinos $J_{\overline{\nu}_e}(E_\nu)$ the event rate (assuming 100% detection efficiency) reads

$$\begin{aligned} \frac{d\mathcal{N}}{dt} &= N_{\rm eff}\ \Delta\Omega\ \int dE_\nu\, J_{\overline{\nu}_e}(E_\nu)\ \sigma(E_\nu) \\ &= N_{\rm eff}\ \Delta\Omega\ \frac{\pi g^2}{4m_e}\ J_{\overline{\nu}_e}\left(\frac{m_W^2}{2m_e}\right)\ , \end{aligned} \tag{4}$$

where $N_{\rm eff} \simeq 6\times 10^{38}$ is the number of target electrons in the effective volume $V \sim 2$ km^3 of the IceCube experiment, and $\Delta\Omega \simeq 2\pi$ is the solid angle aperture [16]. If neutrinos are produced via *pp* inelastic collisions, according to the previous discussion (with $\epsilon_\pi = 0.6$ and $\xi_z = 3$), the antineutrino flux on Earth is $E_\nu^2\, J_{\overline{\nu}_e}(E_\nu) = 6\times 10^{-9}$ GeV cm^{-2} s^{-1} sr^{-1}, so that the event rate is $d\mathcal{N}/dt = 4.6$ yr^{-1}. For antineutrinos produced in photopion interactions ($\epsilon_\pi = 0.25$), the expected rate is a factor of 6 smaller, $d\mathcal{N}/dt = 0.8$ yr^{-1}.

Can the expected resonant signal be differentiated from the continuum background? In order to estimate the background, we note that all but the muon decays of the W devolve into an electromagnetic shower in the detector. For the hadronic decays (which constitute 70% of the total), the interaction mean free path of charged pions in ice is orders of magnitude smaller than the pion decay length at TeV energies, allowing a progressive channeling of nearly all the energy into electromagnetic modes through π^0 decay. For the $e^-\overline{\nu}_e$ and $\tau^-\overline{\nu}_\tau$ decay modes, there will be a single electromagnetic burst triggered by the electron interaction or by the τ decay, each however manifesting only half the energy. As a conservative procedure, we will use in our signal estimate only the hadronic events with full energy in the resonant band, giving (in the case of *pp* interactions) a signal $d\mathcal{N}/dt = 3.2$ yr^{-1}. The background will then constitute the non-resonant scattering of ν_e and $\overline{\nu}_e$ within the resonant band. This is calculated as an integral of the flux times the charged current cross section [17] over the resonant acceptance bin ($10^{6.7}$ GeV, $10^{6.9}$ GeV) of the AMANDA detector [18]. The process being off-resonance, the Earth is transparent and so we take $\Delta\Omega = 4\pi$. The number of target nucleons is twice the number of electrons. This procedure yields a background of 0.6 events yr^{-1}. Thus, within 3 years of data accumulation (1/5 of the total lifetime of the experiment), we expect about 2 background events, with a signal of 9.6 events, well above the 99%CL for discovery (corresponding to 6.69 events [19]).

Electron antineutrinos can also be produced through neutron β-decay. This contribution turns out to be negligible. To obtain an estimate, we sum over the neutron-emitting sources out to the edge of the universe at a distance $1/H_0$ [20]

$$\Phi_{\overline{\nu}_e} = \frac{m_n}{8\,\pi\,\epsilon_0\,H_0}\int_{\frac{m_n E_{\overline{\nu}}}{2\epsilon_0}}^{E_n^{\rm max}} \frac{dE_n}{E_n}\ \mathcal{F}_n(E_n)\ , \tag{5}$$

where $\mathcal{F}_n(E_n)$ is the neutron volume emissivity and m_n the neutron mass. Here, we have assumed that the neutrino is produced monoenergetically in the neutron rest frame, i.e., $\epsilon_0 \sim \delta m_N(1 - m_e^2/\delta^2 m_N)/2 \sim 0.55$ MeV, where $\delta m_N \simeq 1.30$ MeV is the neutron proton mass difference. An upper limit can be placed on $\mathcal{F}_n$ by assuming an extreme case in which all the cosmic rays escaping the source are neutrons, i.e., $\dot\epsilon_{\rm CR} = \int dE_n\ E_n\ \mathcal{F}_n(E_n)$. With the production rate of ultrahigh energy protons $\dot\epsilon_{\rm CR}^{[10^{10},10^{12}]} \sim 5\times 10^{44}$ erg Mpc^{-3} yr^{-1} [21], and an assumed injection spectrum $\mathcal{F}_n \propto E_n^{-2}$, we obtain

$$E_\nu^2\ \Phi_{\overline{\nu}_e} \approx 3\times 10^{-11}\ {\rm GeVcm^{-2}\,s^{-1}\,sr^{-1}}\ , \tag{6}$$

about 3 orders of magnitude smaller than the charge pion contribution with $\epsilon_\pi = 0.6$. (Note that oscillations will reduce the $\overline{\nu}_e$ flux on Earth by 40% from this value.)

Finally, we note that in the case that pions are produced via $p\gamma \to \Delta^+ \to N\pi$, the event rate for the Glashow resonance cannot be separated from background. Thus, the presence or absence of a signal at the Glashow resonance can be used as a filter for *pp*-dominance at the source.

In summary, we have shown how several years of data collection at IceCube can potentially isolate the dominance of inelastic *pp* interactions as neutrino progenitors in cosmic ray sources. The analysis depends on the sources being optically thin, which can be ascertained if the observed diffuse neutrino flux is in agreement with Eq. (1). Then a signal at the Glashow

resonance will provide a strong marker for *pp*-dominance.

Note added: The previous version of this paper contained a brief discussion of how the flux of neutrinos from optically thin sources can be used as a marker of the cosmic ray Galactic/extra-galactic transition. This topic has received detailed discussion in a separate paper [22].

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